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NEW MODELS FOR ANALYZING THE THERMAL AND DAYLIGHTING PERFORMANCE OF FENESTRATION

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ABSTRACT

Accurate determination of the energy impact of fenestration in nonresidential buildings requires daylighting prediction as well as thermal modeling. Despite the computational power of hour-by-hour simulation programs, they involve trade-offs in accuracy, cost, and flexibility. This paper describes new daylighting and thermal modeling capabilities in DOE-2.1B and planned additions. DOE-2.1B now contains a preprocessor-based daylighting model that is sensitive to daylight availability, site conditions, room and glazing parameters, window management for glare and solar control, and lighting controls. To model more complex designs, the next version of the DOE-2.1 program will have a daylighting model based on stored or user-input coefficients of utilization. A lighting program, named SUPERLITE, provides detailed data on illuminance and luminance distribution throughout interior spaces. Because the solar gains through sophisticated daylighting designs are not now adequately calculated, a procedure based on a library of new heat-gain coefficients is being developed. Using sun and sky simulators, these coefficients will be determined from direct measurements of solar optical properties of architectural devices.

The major experimental procedures and analytical models, along with validation studies of DOE-2.1B and SUPERLITE and sample results from these new modeling tools, are described.

INTRODUCTION

Lighting is a major end use of energy in most nonresidential buildings. Design strategies that reduce electric lighting requirements should thereby reduce annual energy consumption and peak electrical loads and may lessen HVAC loads. Improving lighting design strategies, specifying new, efficient lighting hardware, and improving operation and maintenance of lighting systems promise substantial energy savings. The impacts of these strategies can be estimated accurately using conventional analysis.

The use of natural lighting in buildings represents a more complex analytical problem because daylight is highly variable and is accompanied by solar gain. Adding to the problem are uncertainties in integrating lighting sensors and controls to properly utilize daylight. Measured performance data from buildings could provide a picture of the energy and load savings, but the existing data base is small. If existing buildings cannot provide sufficient guidance in finding solutions, designers must use analytical tools. Despite the increasing number of design tools for energy analysis, none currently in extensive use have demonstrated the ability to analyze the impact of daylighting strategies in nonresidential buildings. This paper describes two new computer models--one for illuminance analysis and one for energy analysis--that show promise as powerful and flexible aids in understanding the role of daylighting in energy-efficient buildings.

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The first of these tools, SUPERLITE, is a computer program that predicts the spatial distribution of daylight illuminance in a building, based on sun and sky conditions, site obstructions, details of fenestration and shading devices, and interior properties. Annual energy use and peak load impact are estimated using a second computer program, DOE-2. The DOE-2.1B program determines the energy impact of daylighting strategies based on hour-by-hour analysis of daylighting availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. The thermal interaction of daylighting strategies is automatically accounted for within the DOE-2 program. When used together, these programs form the basis for improving our understanding of fenestration performance.

Figure 1 shows sample results from an extensive parametric analysis of fenestration performance in office buildings. The study was the first in a series we performed to better understand variations in total energy consumption and component loads as a function of major glazing parameters (U-value, shading coefficient, window area, orientation, climate, lighting load, daylighting strategy, etc)[1].

REQUIREMENTS FOR FENESTRATION ANALYSIS

Even powerful computer models such as DOE-2 and SUPERLITE possess only some of the capabilities required to model fenestration systems accurately and efficiently. The tendency to expand computer models indefinitely by continuous accretion of new subroutines frequently creates cumbersome models that are costly to debug, maintain, and use. The trade-offs between increasing computational accuracy and complexity/cost are not easily resolved. Because a great number of fenestration designs are possible, and many of these are geometrically complex, a purely computational approach to daylighting and thermal analysis was abandoned for a primary computational package that utilizes precalculated or measured data. This approach reduces program complexity and cost without sacrificing modeling accuracy, and makes possible analysis of some designs that would be mathematically intractable. The complete analysis package is shown schematically in Fig. 2.

DOE-2 is the central computational tool used in parametric studies of glazing system performance. In Fig. 2, major new capabilities are shown added to the program. These will to allow analysis of thermal and daylighting performance of complex fenestration systems.

The new daylighting model planned for DOE-2.1 is based on a coefficient-of-utilization calculation. These coefficients are (1) calculated in a preprocessor for simple designs, (2) drawn from a library for more complex but standardized designs, or (3) input by the user for unique designs. The data for the DOE-2 library are derived from (1) SUPERLITE calculations of illuminance distributions for simple and moderately complex designs or (2) measurements from scale models in a sun and sky simulator for mathematically intractable designs. When the number of optically active surfaces is not large and the surfaces are diffuse reflectors, SUPERLITE calculates interior illuminance directly from design parameters. When a daylighting element is geometrically complex (e.g., a honeycomb) or has optically complex reflective or refractive surfaces, the program uses measured angular-dependent luminance data to describe the contribution of the device to room illuminance distribution. Each step leading to the energy analysis of daylighting in DOE-2 (Fig. 2) uses a combination of direct computations and/or measurement-based calculations. This approach provides broad modeling flexibility and facilitates expansion of the program without excessive cost.

The new thermal models to be incorporated into DOE-2 follow much the same approach described for the daylighting model. Modeling the performance of complex fenestration systems in detail necessitates combining new analytical models and new experimental procedures. The operational logic for modeling the control of operable insulating and shading systems has already been added to the program in DOE-2.1B. The goal now is to improve the solar heat-gain calculations to permit analysis of geometrically complex architectural sun-control and shading devices. The solar heat-gain calculation is based on measurement of optical and thermal properties of devices, as illustrated in Fig. 2. Devices composed of elements with small dimensions, such as a louvered shade screen, would be measured directly. For larger devices or architectural solutions, scale models would be tested. The analytical solutions for multilayered homogeneous glazing materials are calculated directly in THERM and converted to the matrix formulation for DOE-2.

The Mobile Window Thermal Test (MoWiTT) facility will provide measured performance data to calibrate the net energy performance predictions from DOE-2 and other energy-analysis models. This facility has been designed to directly measure the component heat transfer from fenestration systems and to begin to quantify the interaction of these systems with building HVAC systems.

A primary objective in developing this analytical approach has been to add the necessary groundwork so that we may later expand capabilities to model a broad range of design solutions without further modifying the structure of DOE-2. Embedding results of experimental measurements within a hierarchy of computational models appears to accomplish this goal.

CAPABILITIES OF THE SUPERLITE PROGRAM

The mathematical basis of the SUPERLITE algorithms has been described previously.[2,3] This program can model a uniform sky, Commission International de l'Eclairage (CIE) standard overcast sky, and CIE standard clear skies with or without direct sun. Based on the luminance distribution of a given sky, the luminances of the ground, adjacent buildings, and other external obstructions are calculated; luminances of each interior surface are then determined. Because the luminance across a surface may vary significantly, each surface can be divided into a number of subsurfaces having luminances that are calculated separately. The angular dependence of transmittance through glazing materials is calculated. Once the luminances of all interior and external surfaces have been calculated, the work-plane illuminance is determined by integrating the surface luminances over the appropriate solid angles.

A major advantage of SUPERLITE over other daylighting computational models is its capability for modeling nonrectangular surfaces and other complex geometries. The program will model arbitrary room shapes such as an L-shaped room (Fig. 3), a room with internal partitions, or a room with external obstructions. Windows can be of any trapezoidal shape with an arbitrary tilt angle. Various types of diffusing curtains and draperies can be modeled. Overhangs or fins with opaque, translucent, or semitransmitting materials can also be modeled, permitting analysis of simple light shelves or lightwells. Optical properties determined from model measurements allow modeling of complex sunshading systems such as egg-crate louvers. Additional modifications will allow modeling electric lighting systems combined with daylighting strategies.

Luminance and illuminance values from the program can be output in tabular format or on contour plots, or daylight factors can be generated by an auxiliary graphics program. Contour plots produced by SUPERLITE for an L-shaped room and for a large room with a light shelf are shown in Figs. 3 and 4 respectively.

DOE-2 DAYLIGHTING MODEL CAPABILITIES

DOE-2.1B daylighting simulation determines the hourly, monthly, and yearly impact of daylighting on electrical energy consumption and peak electrical demand; the simulation also determines the impact on cooling and heating requirements and annual energy cost. It accounts for daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. Development of a daylighting model for DOE-2 is based on a compromise of competing requirements for (1) maximizing accuracy, (2) minimizing computational time and cost, (3) minimizing input requirements, and (4) maximizing versatility. A primary concern has been to develop a model that can be expanded to study virtually any architectural daylight strategy. This capability is important because DOE-2 is used frequently to analyze large, complex buildings that incorporate innovative designs. Because completing and debugging major modifications to DOE-2 are time-consuming, the daylighting model in DOE-2.1B should not only model standard room conditions but also accommodate expansion without the need for major modifications. The operation and capabilities of the DOE-2.1B daylighting model and work under way to expand the daylighting and thermal modeling capabilities for complex fenestration systems are described in the next four sections.

Daylight Calculation Model

The DOE-2.1B daylighting calculation has three major stages. First, daylight factors for each window are calculated by a preprocessor for use in the hourly loads calculation (Fig. 5). The user first specifies the coordinates of one or two reference points in a space. To obtain the windows' contribution of direct light to the illuminance at the reference points, DOE-2 integrates a sky luminance function over the area of each window. The program also calculates the contribution of interreflected light from the walls, floor, and ceiling that reaches the reference points using a split-flux approximation to determine an average value for the room. Luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices, and external obstructions are taken into account. The calculation is carried out for standard CIE overcast sky and for 20 CIE clear skies with solar altitude and azimuth values covering the annual range of sun positions. Analogous factors for discomfort glare are also calculated and stored.

In the second stage, a daylighting calculation is performed for each daylight hour of the year (Fig. 6). The illuminance from each window is found by interpolating the stored daylight factors, using the current-hour sun position and cloud cover, and then multiplying by the current-hour exterior horizontal illuminance. If using the glare-control option, the program will assume that window blinds or drapes are closed to lessen glare below a predefined comfort level. A similar option assumes that window shading devices are operated manually or automatically to control solar gain if transmitted sunlight exceeds a specified value.

In stage three (Fig. 6), the program, by simulating the lighting control system (which may be stepped or continuously dimming), determines the energy needed to make up any difference between the calculated daylight illuminance and the specified design illuminance. Each thermal zone can be divided into two independently controlled lighting zones. Both uniform lighting and task-ambient systems can be modeled. Finally, the zone lighting requirements are transferred to the DOE-2 thermal calculation, which determines hourly heating and cooling loads as well as monthly and annual energy use. Additional details of the calculation procedures can be found in Ref 4.

DOE-2 Daylighting Output Reports

Table 1 shows three sample DOE-2 daylighting reports for a south-facing office module in New York City. The module, which is approximately 20 ft (6.2 m) wide, 30 ft (9.2 m) deep, and 10 ft (3.1 m) high, has a 5-ft (1.5-m) high strip window with 3-ft (0.9-m) sill height and 90% transmittance. Drapes with 35% transmittance are automatically closed if direct solar transmission exceeds 20 Btu/ft^2·hr (6.4 W/m^2) or if glare is excessive. The module has two independently controlled lighting zones with reference points 10 ft (3.1 m) and 25 ft (7.7 m) from the window wall and with design illuminance of 50 fc (538 lux). Each lighting zone has a continuously dimmable control system that dims linearly from 100% light/100% power to 20% light/30% power. For the example shown in Tab. 1, the control point closest to the window determines lighting energy savings in the outer half of the module; the inner control point is not used.

The data in these reports describe the role of daylighting in the building in detail. Table 1A provides the type of monthly and annual summary data useful in estimating the savings and cost-effectiveness of a daylighting strategy. The hourly average energy savings given in Tab. 1B provide details of the hourly/monthly pattern of daylight savings. A frequently observed pattern is one in which savings are maximized at midday, but early morning and late afternoon values are well below maximum. Adding glazing in these cases will save little extra lighting energy and may significantly increase cooling loads. These results can be observed zone by zone and for the entire building. Table 1C provides statistics on the frequency of occurrence of various interior daylight illuminance values and on the cumulative probability of exceeding each value. Without rerunning the DOE-2 program, the user can quickly estimate the change in daylighting savings if a design illuminance value is changed or the lighting control strategy is altered.

Other DOE-2 daylighting reports (not shown) give hourly values for exterior and interior daylight illuminance and reductions in lighting power for user-specified time periods.

Daylighting Model for Future DOE-2.1 Version

The DOE-2.1B program calculates interior illuminance for conventional window designs by using a preprocessor calculation and assuming that sun-control systems, such as shades, drapes, and blinds, are ideal diffusers. The program is being expanded to model geometrically complex sunshading solutions such as light shelves, horizontal or vertical louvers, and unique architectural spaces such as large atria.

Because direct calculation of interior illuminance from complex sunshading systems is computationally difficult (and sometimes impossible), a new coefficient-of-utilization model, based on data calculated or measured outside the DOE-2 program, was developed. This new model will be implemented in several ways. Some designs can be standardized (e.g., horizontal flat-louver system) but may be too complex to calculate in DOE-2. These designs would be precalculated by SUPERLITE (for a range of louver reflectance values, width/spacing ratios, etc.) and stored in DOE-2. When generating values for specific products rather than for generic designs is important, SUPERLITE could be used as a preprocessor to DOE-2 and would generate the specific coefficients directly.

A second category includes daylighting designs that can be standardized but may be too complex to calculate using an existing computational model (e.g., complex curved, semispecular light shelves). In this instance, the required illuminance data will be generated from scale models in the sky simulator at Lawrence Berkeley Laboratory (LBL); results will be converted to coefficients that are stored in the DOE-2 library.

A third category includes unique designs not found in the DOE-2 library. In this case, a user can develop the required data from model studies, convert these data into a format compatible with the coefficient-of-utilization calculation, and input the results directly into the program library. Each user can thus create a personal library of custom designs for evaluation.

Each of these options requires a series of systematic calculations or measurements under a full range of overcast, clear-sky, and direct-sun conditions. The coefficient-of-utilization model extends the calculation method now used by the Illuminating Engineering Society for daylighting calculations[5], but includes five coefficients that are sensitive to illumination from the ground, sky, and sun. Basic data for the standard DOE-2 library are being developed from an extensive series of parametric analyses using SUPERLITE and from systematic model tests in the LBL sky simulator.

Fenestration Thermal Model for DOE-2.1

If the energy and load impacts of complex fenestration systems are to be adequately analyzed, the daylight contribution must be properly modeled and the thermal loads must be accurately analyzed. None of the major hour-by-hour energy analysis programs account for the solar gain through geometrically complex fenestration. It is thus necessary to develop a new computational model to determine solar heat gain from complex fenestration systems. The new heat-gain model is similar to the new coefficient-of-utilization daylighting model described previously.

Solar heat gain (SHG) is calculated by splitting the incident solar energy into three components: (1) direct solar radiation, (2) sky diffuse radiation, and (3) ground diffuse radiation. This differentiation is important if systems such as operable louvers are to be modeled accurately. A separate SHG factor will be developed for each component of each fenestration system. Because multiple fenestration devices may be used on a single aperture, the approach must predict the performance of individual devices in series. Solar heat gain through a complex fenestration system at a given time will be determined by:

$$\mathrm{SHG} = I_D(\Theta)T_D(\Theta) + I_{s,d}T_{s,d} + I_{g,d}T_{g,d} + \sum_{j=1}^{3} I_j \sum_{i=1}^{n} N_i A_{ij} \qquad (1)$$

where

$I_D(\theta)$	=	incident direct beam irradiance
$T_D(\theta)$	=	net transmittance for direct beam based on incident angle
$I_{s,d}$	=	incident sky diffuse irradiance
$T_{s,d}$	=	net sky diffuse transmittance
$I_{g,d}$	=	incident ground diffuse irradiance
$T_{g,d}$	=	net ground diffuse transmittance
$\sum_{j=1}^{3} I_j \sum_{i=1}^{n} N_i A_{ij}$	=	net inward-flowing absorbed energy, summed over three irradiance components in each of n absorbing layers

All transmitted components are calculated from optical properties of the devices using a matrix computation that accounts for the interreflectance between glazing layers or shading devices in series.

Because determining the optical properties for separate solar components in an outdoor calorimeter is impractical and calculating many of the values directly is impossible, laboratory measurements are used. Each incident solar component can reach the interior by two pathways: (1) transmission through the aperture, or (2) absorption in the fenestration system and re-radiation and convection to the interior. The transmitted components are determined by a series of optical measurements. Transmission measurements for beam radiation as a function of angle of incidence are made by mounting the device in the opening in a large integrating sphere and illuminating it with an exterior radiant source. The transmittance of the device is the ratio of two signals from a set of detectors in the sphere--one with the device in place and the second with the opening empty. Front and back reflectance measurements will be made by illuminating the device, scanning the radiance over a hemisphere, and integrating the resultant values. Both sets of measurements are made using a sun simulator with a collimated beam at varying incident angles and with a diffuse source in the sky simulator. The absorbed component can be calculated directly if the transmittance and reflectance are known.

Part of the absorbed component will be transferred to the interior space; the rest will be lost to the outdoors. This split will be determined using a calibrated hotbox. The device to be tested will be mounted in the proper location relative to the glazing and the entire assembly will be installed in a hotbox. First the hotbox will be operated normally to establish a base-case conductance; the shading device will then be electrically heated to simulate the absorbed solar component. The resulting reduction in heater power to the hotbox, relative to the total input power to the shading device, is the inward-flowing fraction of absorbed energy. The accuracy limitations of summing contributions from absorbing layers in series require additional study.

MODEL VALIDATION

Extensive validation studies are required to build confidence in the predictions from these analysis tools. Each of the major computational modules has been or is being tested by comparison with more detailed computer models and with experimental data. Validation of predictions of total fenestration performance awaits calibration of the Mobile Window Thermal Test facility.

Daylighting Models

Several types of validation studies have been undertaken for the computer models. In one, the models are tested by running a series of parametric analyses to test the sensitivity of each calculation process to key design parameters. For example, one test series might examine the influence of window size, window transmittance, and interior surface reflectance under a variety of sun and sky conditions. In another, the results of one program are compared with those of the other program and daylighting models. Finally, calculated results from both SUPERLITE and DOE-2 are compared with an extensive series of measurements made on scale models in the LBL sky simulator.[6] This 24-ft (7.4-m) diameter indoor facility permits testing under uniform, overcast, and clear-sky conditions (Fig. 7). Using this artificial sky provides advantages over using outdoor tests: (1) the direct illuminance from the sun can be separated from the clear-sky distribution, (2) the reflectance of the ground can be easily controlled, and, most important, (3) the sky luminance distributions are stable and reproducible.

A small, single-occupant office model and a large, open-landscaped office model have been tested under a variety of sky conditions. The graphs in Figs. 8 through 11 compare daylight factors from SUPERLITE and DOE-2 calculations with measurements under the artificial sky along the centerline of the models; results are shown for clear and overcast conditions for both small and large models. The comparison shows good agreement throughout the cross section of the room. Additional comparisons with outdoor model tests are in progress.

Thermal Models

The thermal models in DOE-2 must accurately predict performance for a broad range of new window systems. Some of these new systems employ multiple glass and plastic layers, transparent low-emittance coatings, and low-conductance gas fills. These systems can be modeled using an extension of existing algorithms and are validated by comparison with heat transfer predicted from THERM, a detailed window heat-transfer model based on the algorithms described in Ref 7. Heat-transfer predictions from THERM have been validated by comparison with results from a calibrated hotbox.[8]

The performance of complex window systems under incident sunlight must be validated in an outdoor facility that accounts for solar gain, temperature effects, and other energy-related interactions. A Mobile Window Thermal Test facility has been built for this purpose.[9] The facility contains two highly instrumented, side-by-side test chambers, the thermal properties of which can be altered to simulate a range of building conditions. This facility permits direct measurement of the thermal impact of fenestration on HVAC systems and allows the thermal impact of daylighting strategies to be measured. The primary objective of the facility is to develop a data base on fenestration performance at a level of detail that allows hour-by-hour energy analysis programs such as DOE-2 to be validated at the algorithm level. Field calibration of the unit is in progress (Fig. 12).

SUMMARY AND FUTURE DIRECTIONS

The two computer models described here represent powerful and complementary design tools that will improve understanding of the role of daylighting in making buildings energy efficient. Recognizing the strengths, weaknesses, and limitations of any design tool is required to use that tool properly. SUPERLITE is a lighting design tool that calculates the detailed interior daylight distribution patterns resulting from both simple and complex fenestration designs under a variety of climatic conditions. When the capability for modeling electric lighting is added, examination of the interaction and integration of daylight and electric lighting control strategies will be possible. The primary advantage of this model over other computational models is its ability to analyze geometrically complex but architecturally interesting concepts accurately. This capability is being expanded to model complex shading systems, specular reflectors, and other nonstandard design alternatives based on measurements of device luminance distributions.

The daylighting model in DOE-2.1B has been designed for flexibility and expansion. Currently, the program calculates interior illuminance of conventional window designs by using a preprocessor calculation and assuming sun-control systems that are ideal diffusers (such as shades, drapes, and blinds). The program is being expanded to allow modeling of more geometrically complex sunshading solutions (such as horizontal or vertical louvers). The expansion is based on results calculated by the SUPERLITE program or determined by model measurements. These results will be stored in a library within the DOE-2 program or may be specified by the user. For one-of-a-kind designs, a user can input daylight coefficients based on model tests of that design. The goal is an energy-analysis model that is highly flexible and responsive to the latest design strategies. In addition, DOE-2's thermal and sun-control modeling capabilities are being expanded to be consistent with improved daylighting modeling. The ability of an energy-analysis model to accurately evaluate trade-offs in heat loss, heat gain, and daylighting benefits requires equivalent accuracy and versatility in treating both the thermal and daylighting aspects of fenestration design.

Earlier versions of DOE-2.1 have been used extensively by larger architectural and engineering firms for routine and state-of-the-art building designs. Both the DOE-2.1B and SUPERLITE programs and supporting documentation are available to the design community. However, both programs are large computer models that require a substantial investment in training. Most buildings are designed using much simpler and more accessible design tools. Thus, these powerful new computer models are also being used to develop the technical basis for simplified design tools that can reproduce most of the accuracy and analytical power of the more complex tools but are less costly and easier to use.

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TABLE 1A

DOE-2.1B Daylighting Summary Report

Sample DOE-2.1B Daylighting Report LS-G--Space Daylighting Summary--for the South-facing office module described in Fig. 1. Times under "report schedule hours" are restricted to the period 8 a.m. and 5 p.m., the hours of major occupancy.

	Percent Lighting Energy Reduction By Daylighting (All Hours)			Percent Lighting Energy Reduction By Daylighting (Report Schedule Hours)			Report Schedule Hours with Sun Up: Average Daylight Illuminance (Footcandles)		Percent Hours Daylight Illuminance Above Setpoint		Average Glare Index		Percent Hours Glare Too High	
Month	Total Zone	REF PT 1	REF PT 2	Total Zone	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2
JAN	17.1	34.3	0.	22.1	44.1	0.	40.3	0.	34.8	0.	8.7	0.	0.	0.
FEB	20.1	40.2	0.	25.3	50.7	0.	46.9	0.	44.8	0.	9.9	0.	0.	0.
MAR	22.5	45.0	0.	27.5	55.0	0.	50.6	0.	57.0	0.	10.4	0.	0.	0.
APR	25.3	50.6	0.	30.2	60.4	0.	55.8	0.	59.3	0.	11.3	0.	0.	0.
MAY	27.6	55.2	0.	32.2	64.4	0.	54.4	0.	45.5	0.	11.4	0.	0.	0.
JUN	28.8	57.6	0.	33.2	66.4	0.	66.5	0.	58.5	0.	12.4	0.	0.	0.
JUL	27.0	54.0	0.	31.2	62.4	0.	65.5	0.	58.4	0.	12.2	0.	0.	0.
AUG	28.6	57.3	0.	33.7	67.5	0.	69.3	0.	71.3	0.	12.9	0.	0.	0.
SEPT	25.9	51.7	0.	30.5	61.0	0.	53.6	0.	56.7	0.	10.9	0.	0.	0.
OCT	24.7	49.3	0.	30.4	60.7	0.	58.6	0.	58.4	0.	11.2	0.	0.	0.
NOV	19.3	38.6	0.	24.6	49.2	0.	45.6	0.	43.3	0.	9.6	0.	0.	0.
DEC	15.5	31.0	0.	19.9	39.8	0.	39.3	0.	36.9	0.	8.5	0.	0.	0.
ANNUAL	23.6	47.2	0.	28.4	56.9	0.	53.9	0.	52.1	0.	10.8	0.	0.	0.

NOTE: 1 fc = 10.76 lux.

TABLE 1B

Summary of Hourly Daylighting Savings

Sample DOE-2.1B daylighting Report LS-H--percent of lighting energy reduction by daylighting vs hour of the day--for the south-facing office module described in Fig. 1.

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Hours
JAN	0	0	0	0	0	0	0	4	16	23	25	28	26	24	22	20	14	10	0	0	0	0	0	0	17
FEB	0	0	0	0	0	0	0	8	19	24	27	29	30	29	28	25	18	9	0	0	0	0	0	0	20
MAR	0	0	0	0	0	0	9	21	25	27	29	30	29	30	29	27	22	15	0	0	0	0	0	0	23
APR	0	0	0	0	0	3	21	28	29	30	32	32	33	31	30	29	25	21	2	0	0	0	0	0	25
MAY	0	0	0	0	0	10	26	30	32	31	32	33	33	33	34	32	29	26	5	0	0	0	0	0	28
JUN	0	0	0	0	1	10	26	30	33	34	33	35	34	32	34	34	31	24	13	1	0	0	0	0	29
JUL	0	0	0	0	0	7	24	30	31	31	32	32	31	32	33	30	30	27	6	1	0	0	0	0	27
AUG	0	0	0	0	0	0	23	31	33	34	39	35	35	35	34	33	31	22	3	0	0	0	0	0	29
SEP	0	0	0	0	0	3	17	29	29	30	31	32	33	31	30	30	29	18	1	0	0	0	0	0	26
OCT	0	0	0	0	0	0	8	26	28	31	33	34	33	32	30	27	24	2	0	0	0	0	0	0	25
NOV	0	0	0	0	0	0	5	16	26	28	28	30	29	27	25	24	4	0	0	0	0	0	0	0	19
DEC	0	0	0	0	0	0	0	4	16	21	23	25	25	24	22	19	4	0	0	0	0	0	0	0	15
ANNUAL	0	0	0	0	0	4	17	26	26	29	30	31	31	30	29	28	20	12	3	0	0	0	0	0	24

NOTE-The Entries in This Report Are Not
Subject To The Daylighting Report Schedule

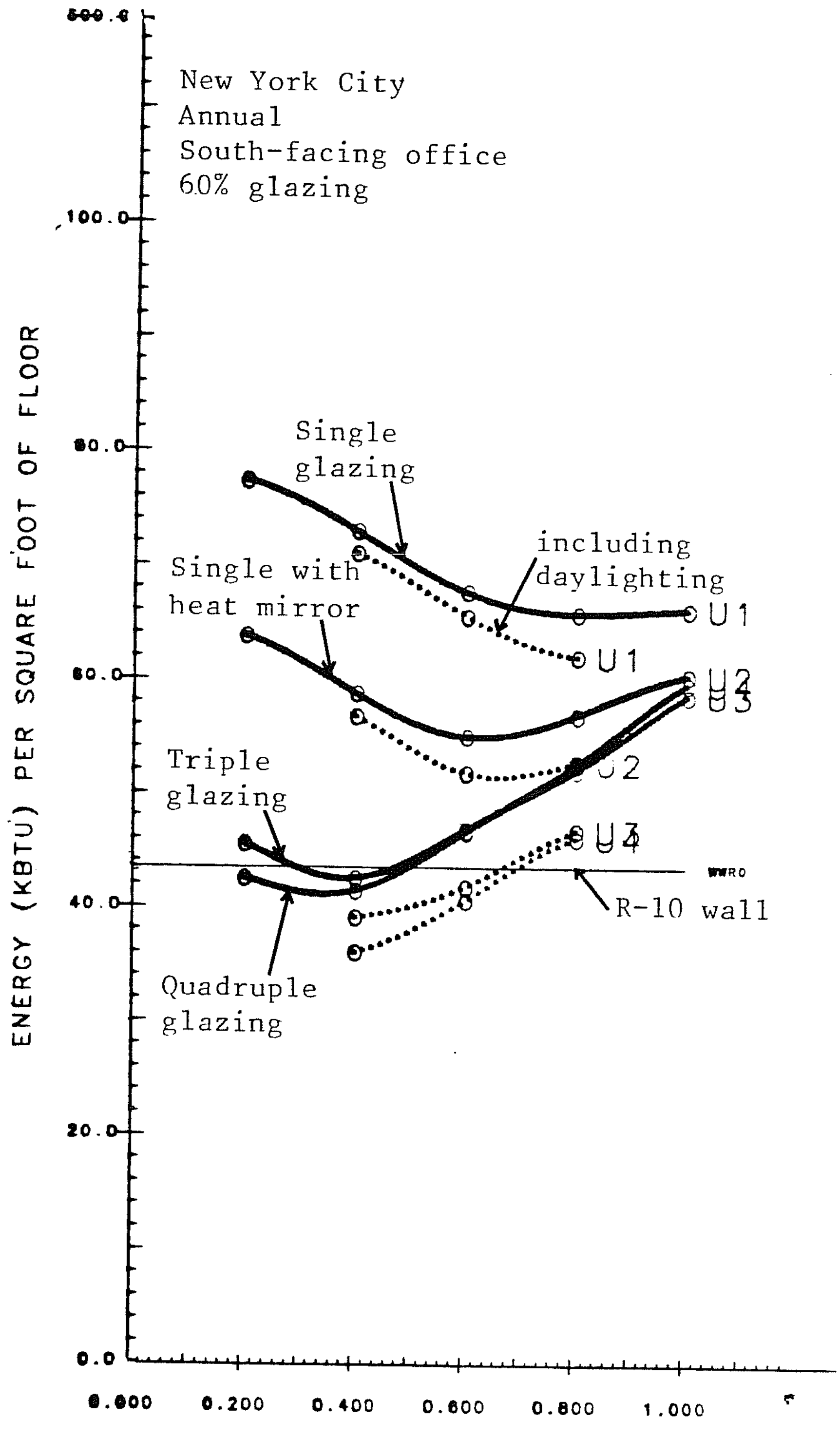
TABLE 1C

Frequency of Interior Daylight Illuminance

Sample DOE-2.1B daylighting program Report LS-J—Daylight Illuminance Frequency of Occurence—for the south-facing office module described in Fig. 1.

		Percent of Hours In Illuminance Range									Percent of Hours Illuminance Level Exceeded								
		Illuminance Range (Footcandles)									Illuminance Level (Footcandles)								
Month	REF PT	0 — 10	10 — 20	20 — 30	30 — 40	40 — 50	50 — 60	60 — 70	70— 80	80 -Above	0	10	20	30	40	50	60	70	80
JAN	-1-	28	11	6	9	11	5	8	4	18	100	72	61	55	46	35	30	22	18
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	-1-	17	12	5	9	13	7	11	10	17	100	83	71	66	58	45	38	27	17
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	-1-	15	8	5	5	10	17	15	11	14	100	85	77	72	67	57	40	25	14
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	-1-	7	10	4	7	13	16	16	13	15	100	93	83	80	72	59	44	28	15
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	-1-	4	5	8	13	25	14	8	7	16	100	96	90	83	70	46	32	23	16
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUN	-1-	0	6	4	13	18	13	7	8	31	100	100	94	90	77	59	46	39	31
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	-1-	3	5	5	8	20	11	8	9	30	100	97	92	87	78	58	47	39	30
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUG	-1-	0	1	3	9	15	21	16	7	27	100	100	99	95	87	71	50	34	27
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEPT	-1-	12	5	5	8	13	20	13	9	16	100	88	83	78	70	57	37	24	16
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCT	-1-	8	11	4	8	11	9	8	11	30	100	92	81	77	70	58	49	41	30
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOV	-1-	22	13	6	7	9	8	7	8	20	100	78	64	59	52	43	35	28	20
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEC	-1-	29	13	8	9	4	10	5	3	19	100	71	58	50	41	37	27	22	19
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANNUAL	-1-	12	8	5	9	14	13	10	8	21	100	88	80	74	66	52	40	29	21
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NOTE: 1 fc = 10.76 lux.
The hours considered in this report are those with sun up and daylighting report schedule on.



XBL 823-8274A

Figure 1. Energy requirements for a south-oriented office module in New York City.

U1 = Normal single glazing, nominal 6.28 $W/m^{2o}C$.

U2 = Single glazing with low-emissivity coating, nominal 4.33 $W/m^{2o}C$.

U3 = Normal triple glazing, nominal 1.8 $W/m^{2o}C$.

U4 = Nominal 1.2 $W/m^{2o}C$.

Solid line = Energy use with no utilization of daylighting.

Broken line = Energy use with daylighting utilization.

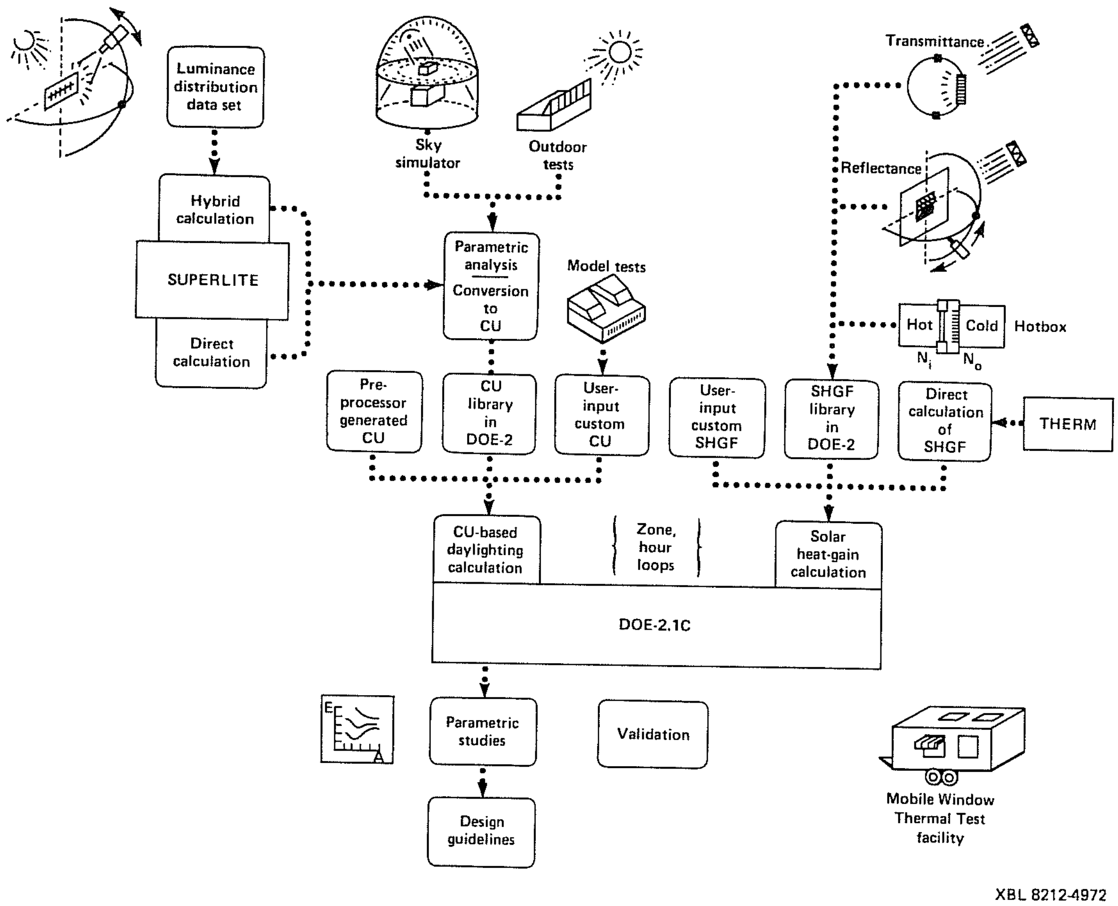


Figure 2. Schematic diagram of DOE-2.1C planned fenestration modeling capabilities. Input is based on direct computation, or calculations based on laboratory or field measurements, and is stored in DOE-2 or entered by the user. Input is validated by model testing and in-situ testing by MoWiTT.

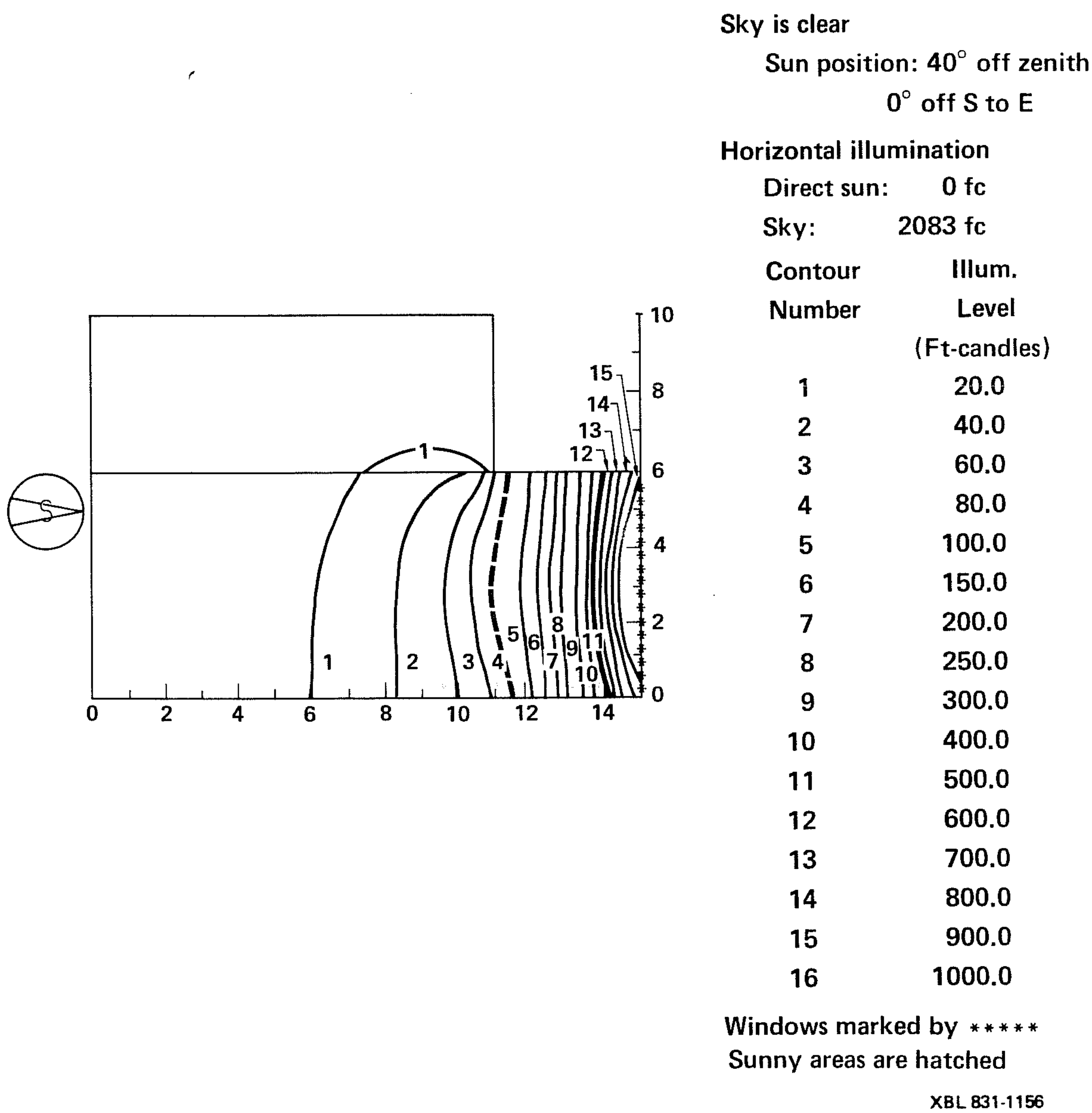


Figure 3. SUPERLITE illuminance contour plot for an L-shaped room. Contours of 100 fc (dashed) and 500 fc (heavy) are highlighted. Hatching shows where sunlight falls on floor.

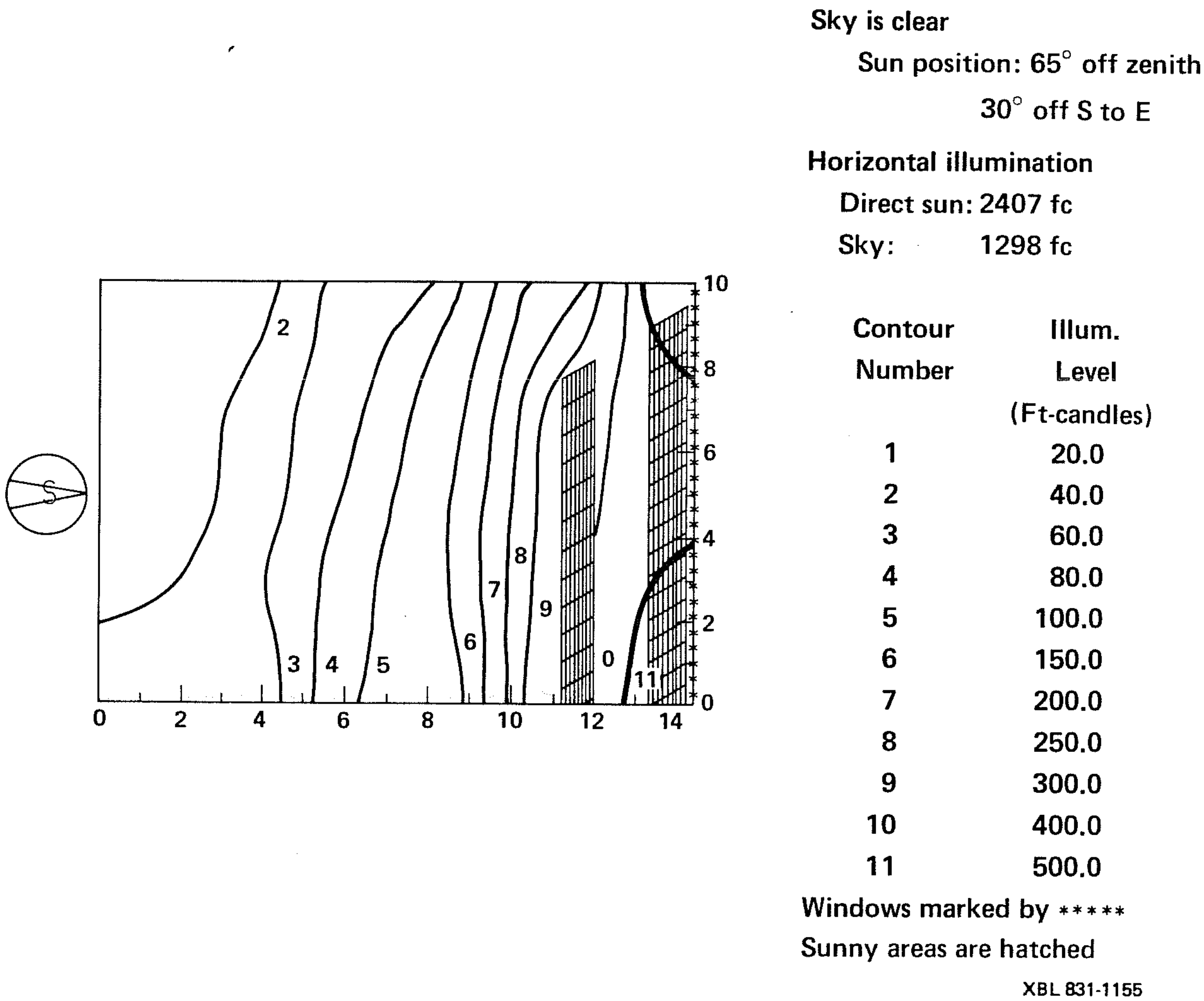


Figure 4. SUPERLITE contour plot for a model having a clerestory and light shelf and with direct sun. Contours of 100 h-fc (dashed) and 500-fc (heavy) are highlighted. Hatching shows where sunlight falls on floor.

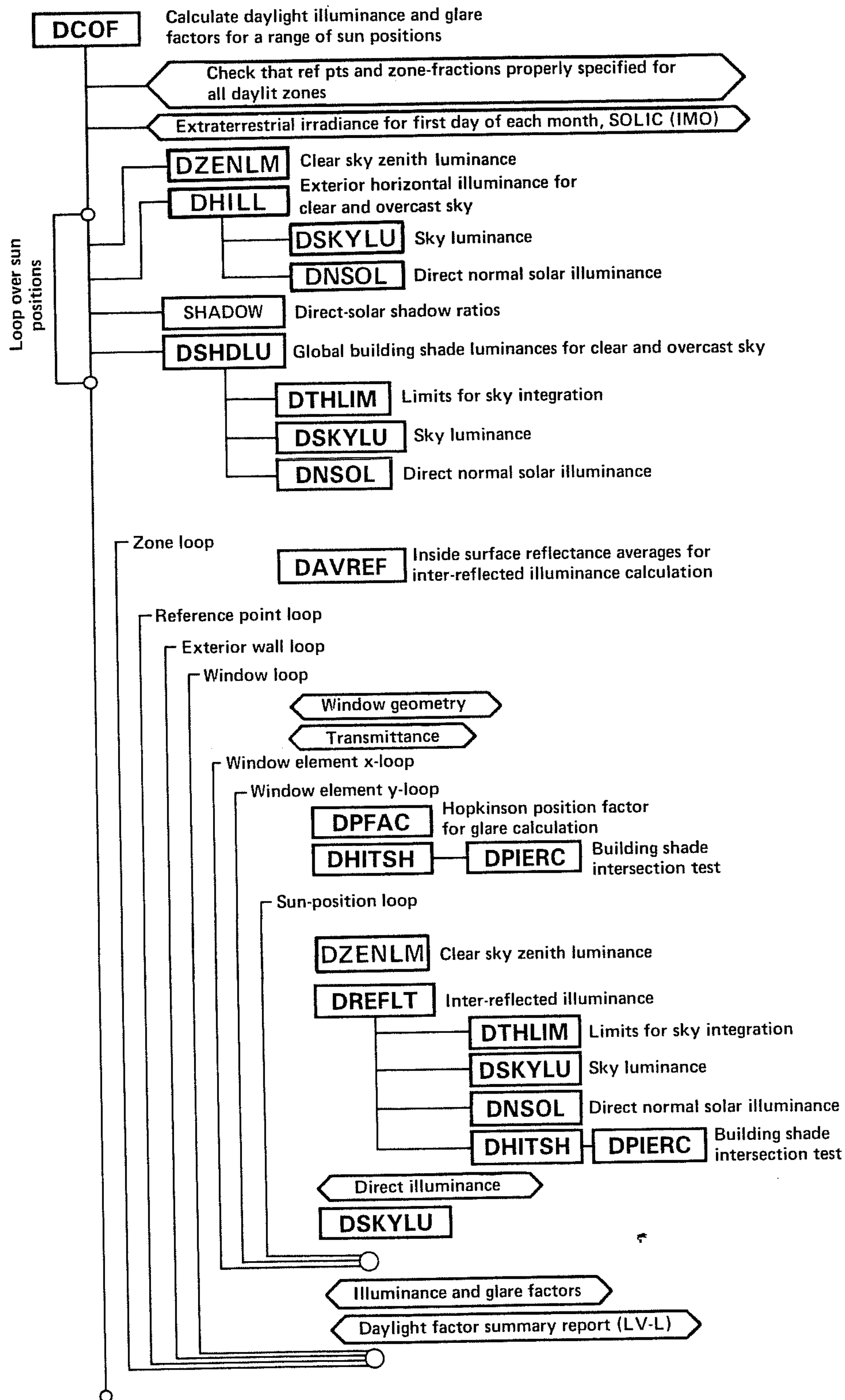
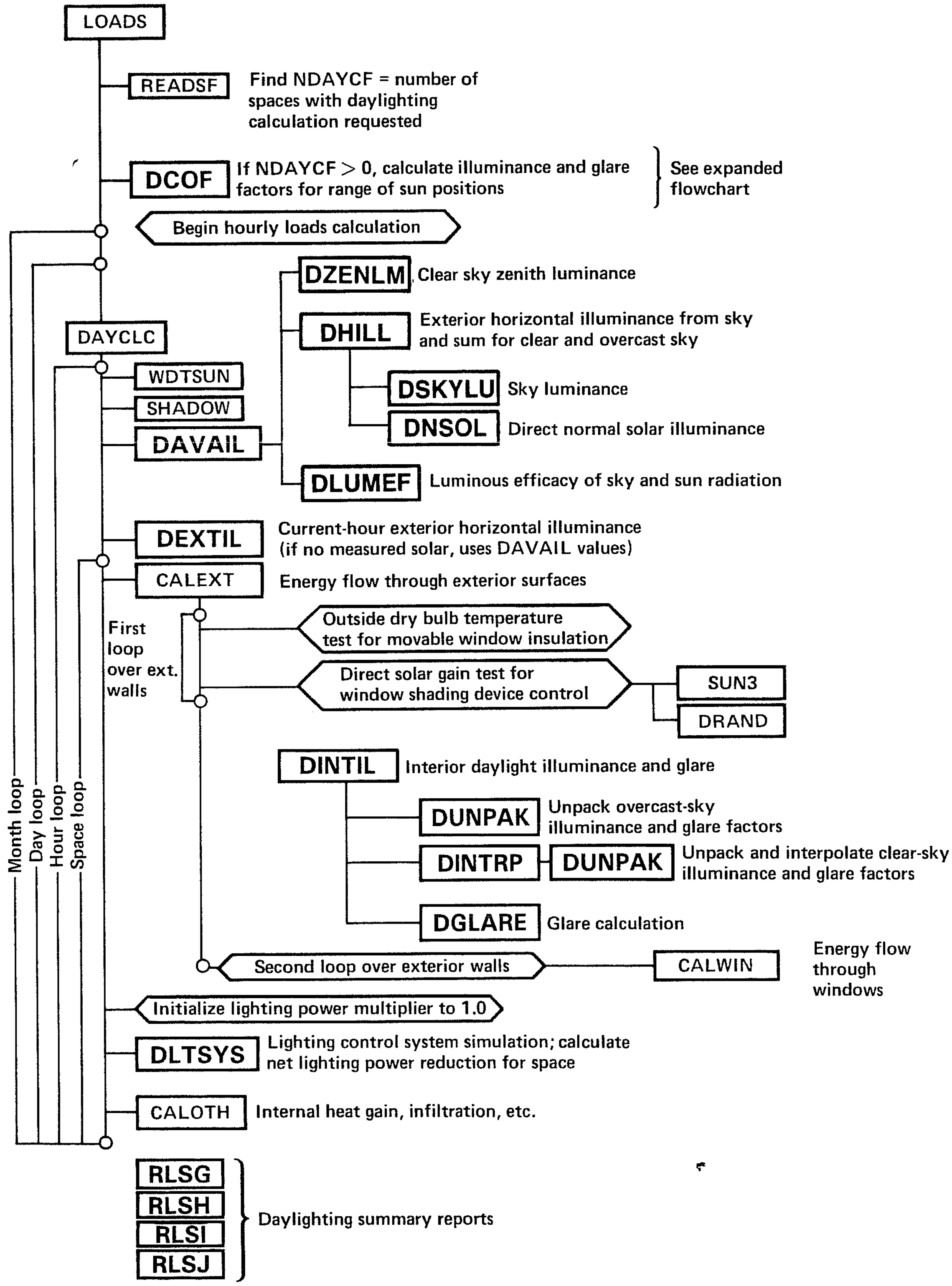
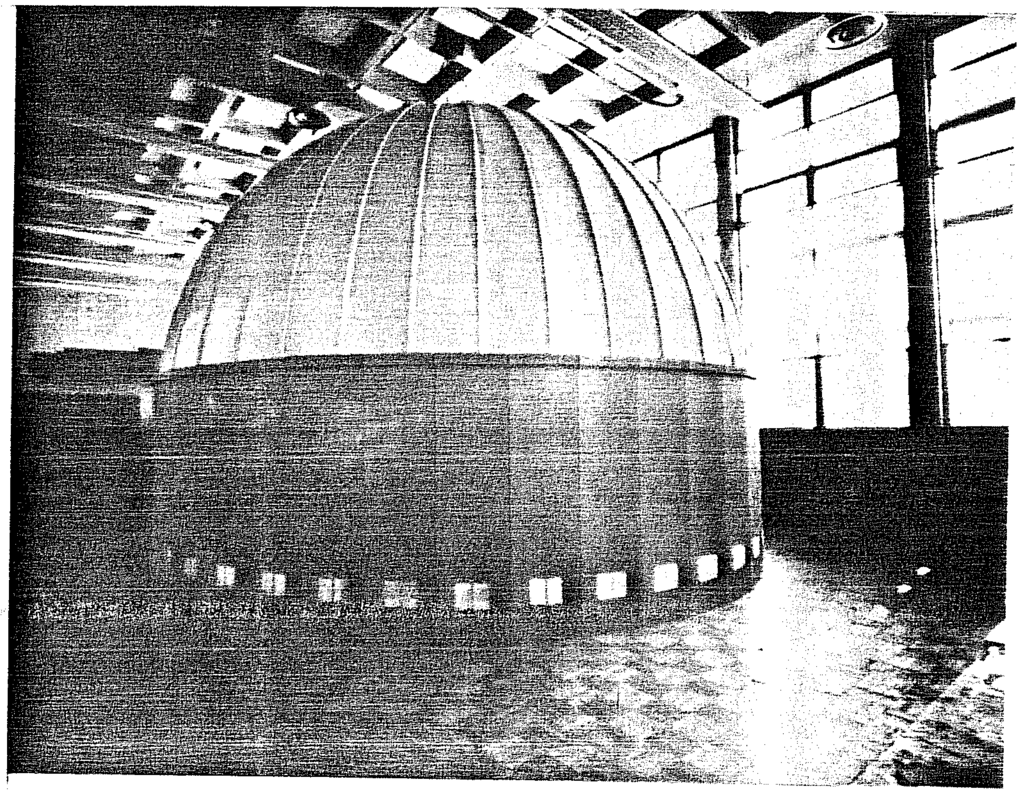


Figure 5. Flowchart for DOE-2.1B daylighting preprocessor. Daylighting subroutines are in boldface.



XBL 827-7145

Figure 6. Flowchart for DOE-2.1B daylighting calculation. Daylighting subroutines are in boldface. Some nondaylighting LOADS subroutines are also shown.



XBB 804-5182

Figure 7. Exterior view of a 24-ft (7.4-m) diameter hemispherical sky simulator.

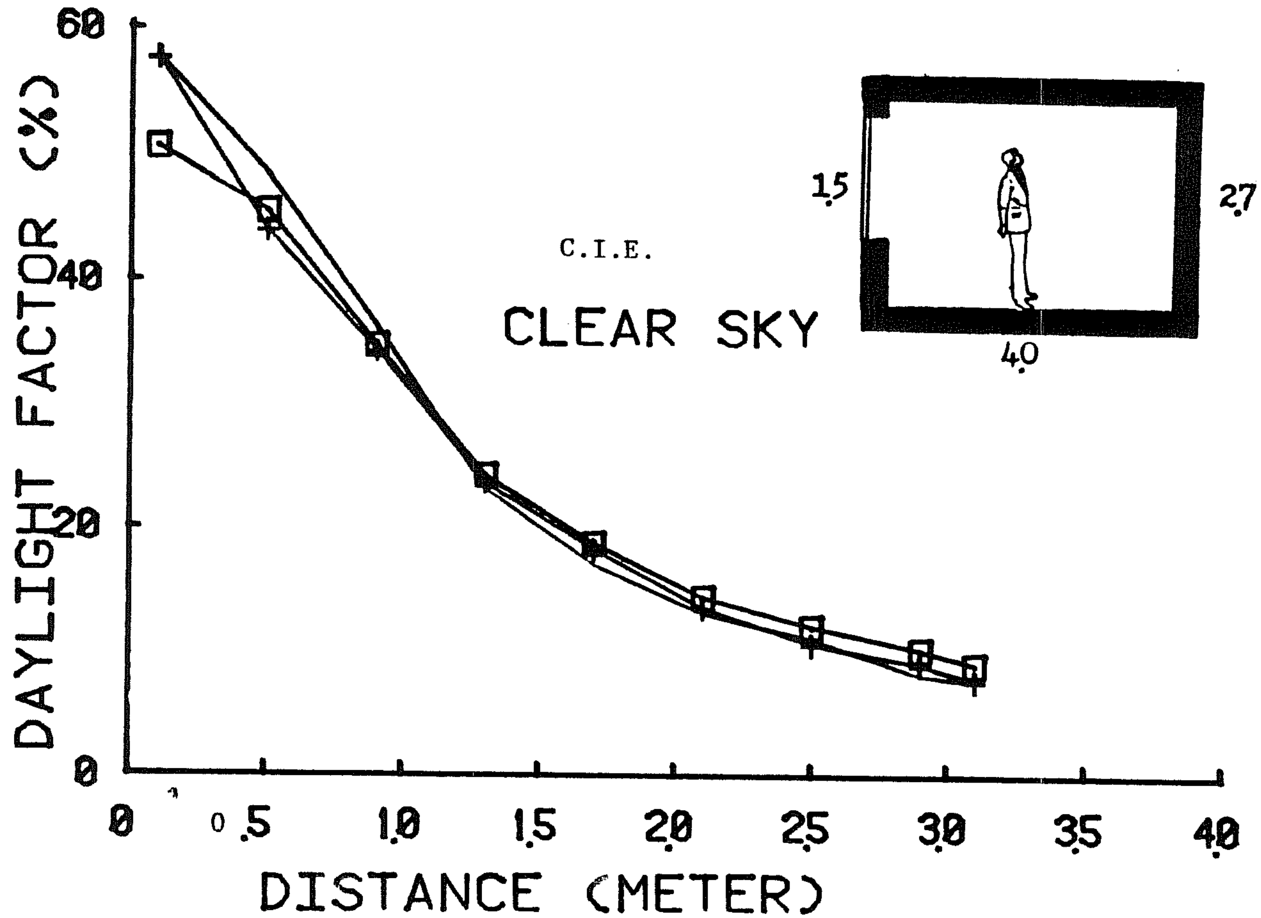


Figure 8. SUPERLITE (+) and DOE-2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude of 50^o, and azimuth of 0^o; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

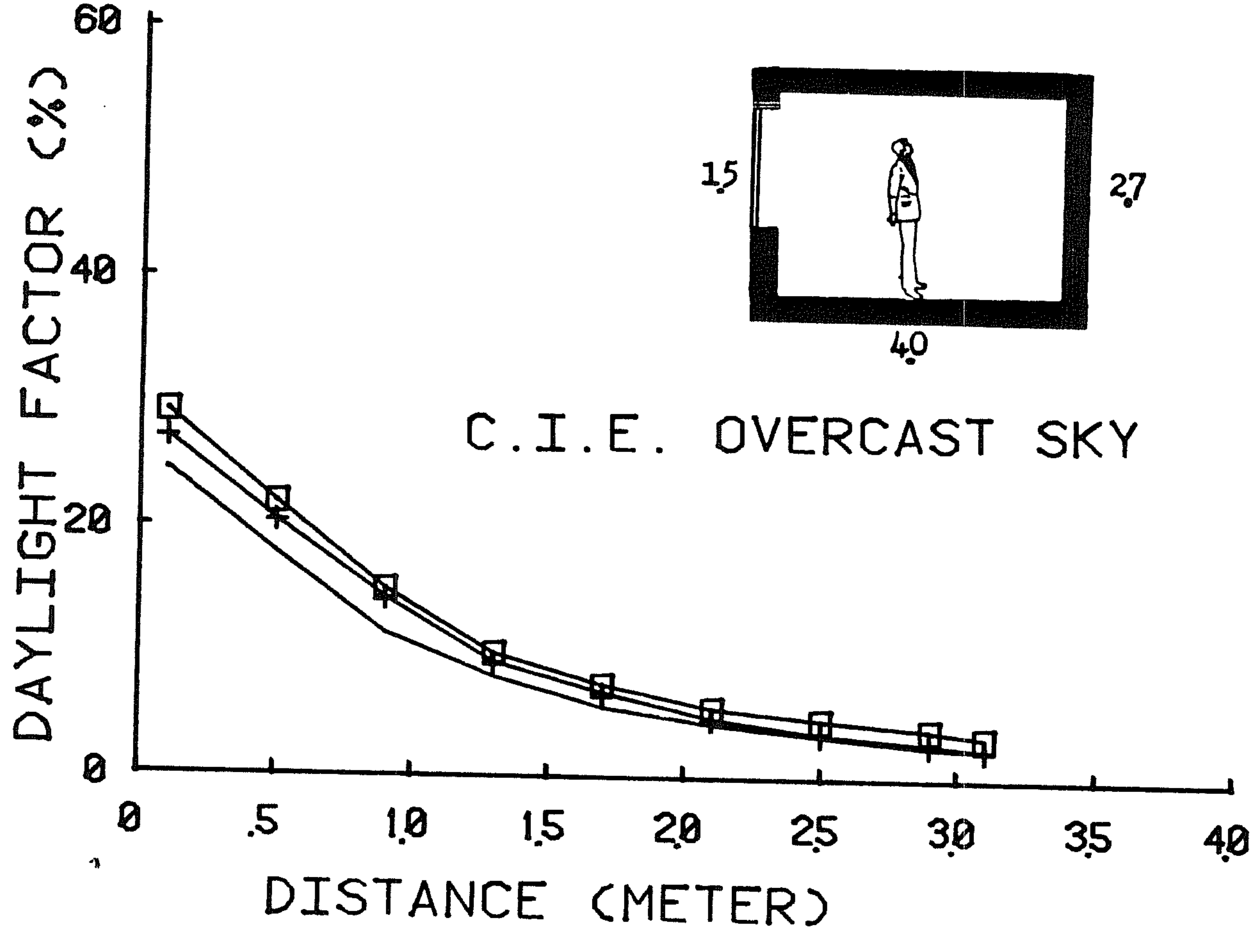


Figure 9. SUPERLITE (+) and DOE-2 (□) predictions under CIE overcast sky compared with sky-simulator measurements (-). Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

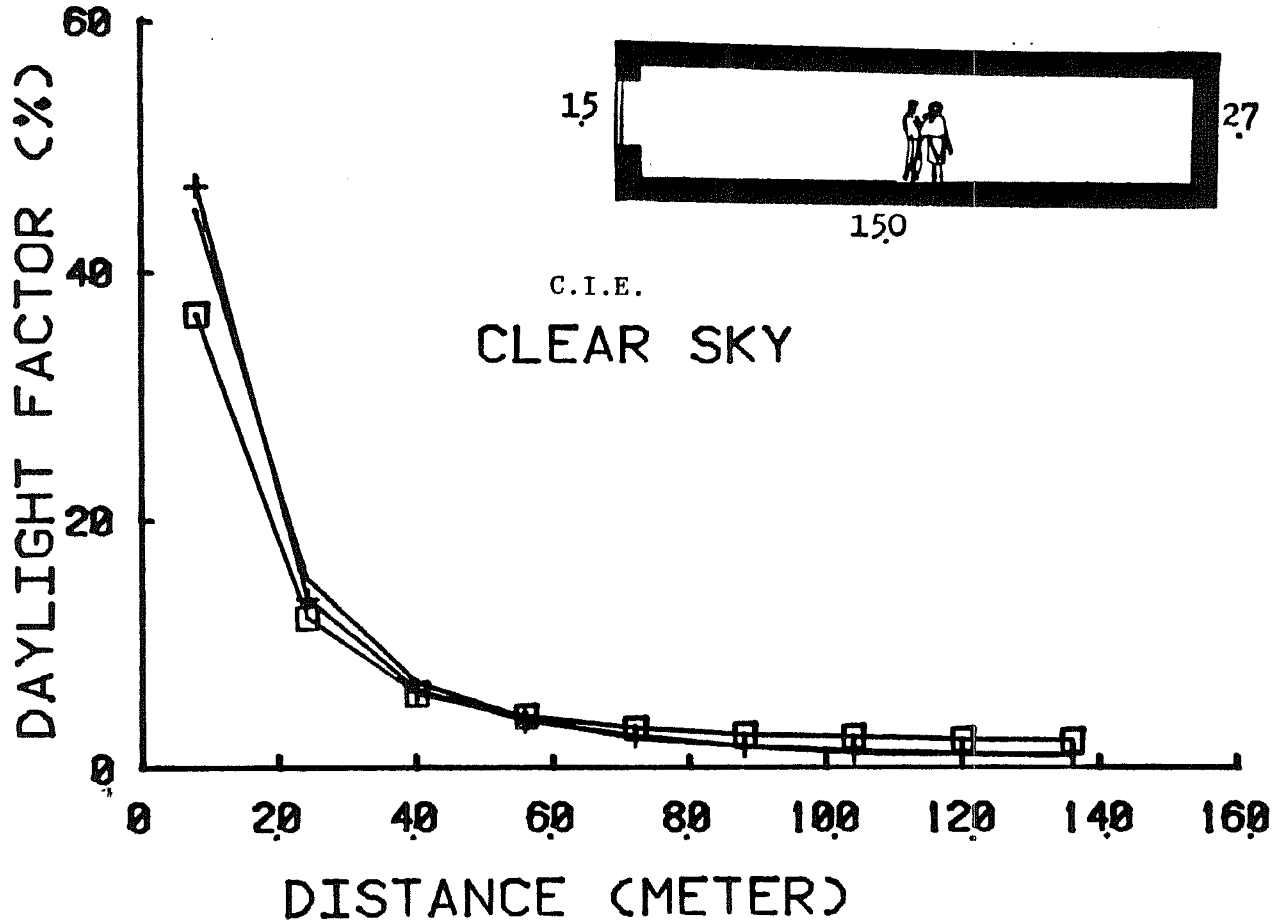


Figure 10. SUPERLITE (+) and DOE-2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude of 50^{o}, and azimuth of 0^{o}; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

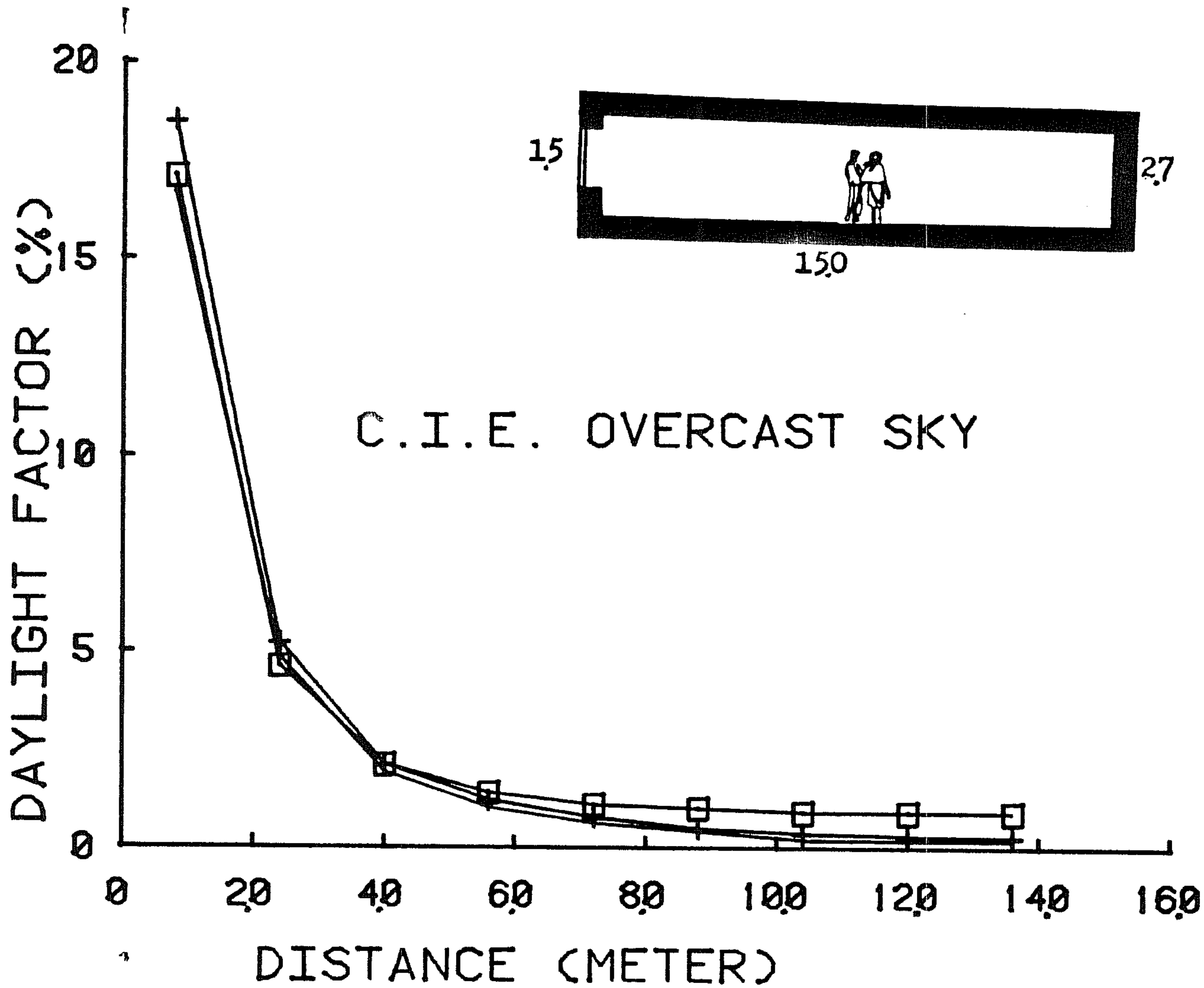
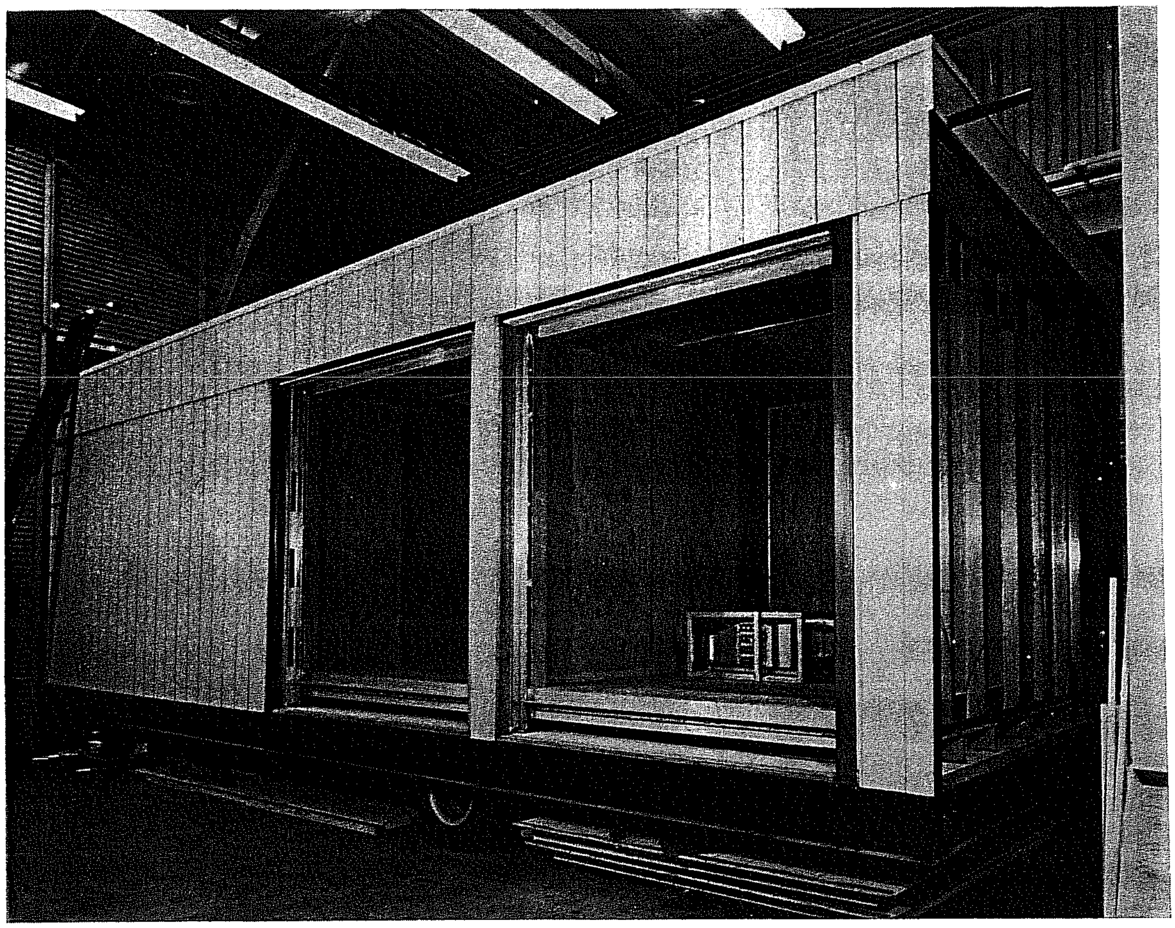


Figure 11. SUPERLITE (+) and DOE-2 (□) predictions under CIE overcast sky compared with sky-simulator measurements (-). Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls and 80% for ceiling. Glass transmittance is 90%.



CBB 825-5379

Figure 12. Exterior view of the MoWiTT facility, showing the side-by-side test chambers.